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Skafte, Theis Løye; Hjelm, Johan; Blennow, Peter; Graves, Christopher R.

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Quantitative review of degradation and lifetime of solid oxide cells and stacks

Theis L. Skafte (1,2), Johan Hjelm (2), Peter Blennow (1), Christopher Graves (2)
(1) Haldor Topsoe A/S
Haldor Topsøes Allé 1, 2800 Kgs. Lyngby/Denmark
(2) Department of Energy Conversion and Storage, Technical University of Denmark
Risø campus, Frederiksborgvej 399, 4000 Roskilde/Denmark
Tel.: +45-2552-9534
Fax: NA
tlsk@dtu.dk

Abstract

A comprehensive review of degradation and lifetime for solid oxide cells and stacks has been conducted. Based on more than 50 parameters from 150 publications and 1 000 000 hours of accumulated testing, this paper presents a quantitative analysis of the current international status of degradation and lifetime in the field. The data is used to visualize specific trends regarding choice of materials, operating conditions and degradation rates. The average degradation rate reported is decreasing and is quickly approaching official targets. The database is published online for open-access and a continued updating by the community is encouraged. Furthermore, the commonly reported test parameters and degradation indicators are discussed. The difficulty in standardizing testing due to variations in cell and stack design, materials and intended purpose of the system is acknowledged. A standardization of reporting of long-term single-cell- and stack-tests is proposed.

Introduction

To reach market penetration for the solid oxide cell technology, three aspects are often mentioned as deciding factors: performance, lifetime and costs [1]. These are naturally interlinked, but in truth the situation is far more complicated. On the most fundamental level only one single question needs to be considered, but the answer is not straightforward: Is the value gain higher for this technology compared to an alternative technology? The gain depends on the application, but it will either be electricity (SOFC) or a gas (SOEC). The value of this product depends on the price of electricity and gas in that given situation, but also on other factors, which are relevant for that specific application. The system is thus economically viable if either the product price is higher than the cost of obtaining the product and lower than what the alternative technology can deliver, or if the technology can deliver certain advantages which other, perhaps cheaper, technologies cannot. It quickly becomes complex to consider the cost paid to obtain the product, as such cost analysis would not only need to include fuel gas, raw materials, operation costs, production machinery, research instruments, labor and so forth in the calculations, but also technical parameters such as initial performance (or efficiency), degradation and lifetime of the system.

To assess how far the technology is from a commercial breakthrough and thereby justify further funding, both economic and technical studies are necessary. These are naturally strongly interrelated and both can change the intended business case. Basically, any action taken to improve the business case must be held up against all other possibilities and the one that brings the most value must be prioritized. The present study attempts to map out the current international status of the solid oxide cell technology regarding three of the main technical aspects, namely the initial performance, the degradation, and the lifetime of cells and stacks.

This study was carried out in a quantitative manner, which to the authors' best knowledge has not been conducted before. The database contains an excess of 1 000 000 accumulated test hours from more than 150 tests, and has been published as open-access [2]. The intention was to obtain insights into the most deciding operation- and design-parameters of a solid oxide device. This would bring vital information for assessing and mitigating degradation and increasing lifetime, and thus bring down costs of the product. It turned out to be quite challenging, mainly due to how the reporting of degradation and lifetime is approached in the solid oxide cell community. This issue will be discussed and a standardized protocol for reporting long-term tests will be suggested, so as to raise awareness of how best to assess degradation and lifetime, and compare results between different tests and systems.

1. Degradation mechanisms

Because of the inherent complexity and interrelation between various parts of a cell and even more so, a stack, there exist a multitude of degradation mechanisms that can decrease the value-output of the system. The purpose of this study is not to describe every possible mechanism – as has already been well done by other authors (SOC [3], SOFC [4-8], SOEC [9-12]) – but a brief introduction to some of the most well-known degradation mechanisms follows and these mechanisms are illustrated in Figure 1.

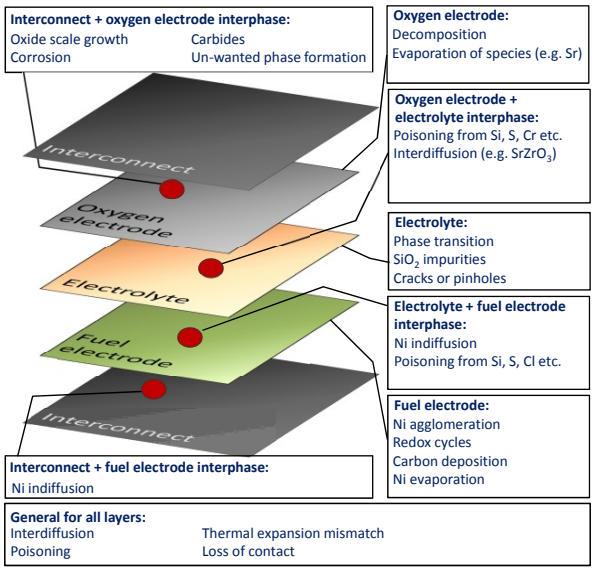

Figure 1: A simplified exploded view of a single-repeating unit (SRU) and a few of the possible degradation mechanisms. A SRU may involve additional layers such as multi-layered electrodes, barrier layers, coatings, sealing layers and/or contacting layers, which are not included in this example.

Interconnects and oxidant side

For the ferritic stainless steel based interconnect (IC) the most well-known mechanisms are chromia scale growth and simultaneous volatilization of the protective chromia scale that forms on its surface during operation. The chromia scale itself has low electronic conductivity where interdiffusion of cation species like Cr, Co, Fe, Mn and Sr at the IC and oxygen electrode (or contact layer) interface will create layers with increased ohmic resistance [13]. For further information the review paper by Shaigan et al. is recommended [14].

The oxygen electrode and surrounding layers often suffers from Cr poisoning [15-19] from the IC and other upstream hot steel components. In fact, this is one of the most often mentioned degradation mechanisms in recent long-term stack tests [20-23] and an effective blocking coating layer is highly desired. Other impurities forming insulating phases are S, P, Cl, Na and Si [24-25]. Phase instabilities and kinetic demixing due to evaporation or enhanced mobility of certain elements is also possible [15].

For cobaltite/ferrite oxygen electrodes, without a barrier layer or with a poor, porous barrier layer, La [26] and Sr [27-28] may cause reactions between the oxygen electrode and the electrolyte. However, the commonly employed barrier layer of Gd-doped CeO_2 (CGO) and popular oxygen electrode La-Sr-Co-Fe-oxide (LSCF) may also suffer from La, Sr and Gd interdiffusion [29-30]. Under high electrolysis current density, formation of micro-bubbles have been reported at the electrolyte interface, but this phenomenon has largely been mitigated by switching from the La-Sr-Mn-oxide (LSM) oxygen electrode to LSCF [31].

Electrolyte and fuel side

Aside from the aforementioned La- and Sr-reactions, the main problems for the electrolyte are related to mechanical or processing issues causing cracks and pinholes, which can lead to other issues such as re-oxidation of reduced Ni. However, the electrolyte can also be affected by impurities, e.g. SiO_2 collecting in the grain boundaries or incorporation of Mn from the oxygen electrode [32].

In many recent single-cell-tests with LSCF oxygen electrodes the component responsible for the highest degradation rate is the fuel electrode. The commonly used Ni- and yttria-stabilized-zirconia composite (Ni-YSZ) can cause catastrophic failure by re-oxidation [33-35] or carbon deposition [36-38], or degrade more gradually by Ni agglomeration [39-41], leading to loss of electrical percolation and triple-phase-boundary (TPB) length, and by poisoning by impurities [42-44], i.e. S [45-47], Si [48], P [49-50] and Cl [51-53].

On the fuel side of the IC, Ni interdiffusion and austenite formation [54], carbide formation [55], sigma-phase formation and oxide scale growth [56-57] can all lead to an increased degradation rate.

In general for all interfaces there may be issues with interdiffusion layers, poor adhesion and loss of contact, especially between the electrodes and the IC. Impurities brought in from the original material, the gasses supplied or during manufacturing processes, are likewise important to consider.

2. Quantitative analysis

The general lack of published data became apparent while collecting data for the following analysis. The intent was to collect data specified in Table 1 for each test.

Table 1: Test information that was logged. **Bold** indicates that the information is often, but not always, available.

General	**Cell and/or stack producer**, **testing organization**, **year of publication**
Cell/stack	**Design type**, components (incl. IC's), **materials**, layer-thickness, -porosity and -tortuosity, particle sizes
Operation	**Testing temperature**, **length of test**, **number of cells**, **size of cells**, **current density**, **initial and final voltage**, initial ASR, **gas types**, gas flow rates, gas purities, gas utilization (e.g. fuel utilization, FU), number of thermal- and load-cycles
Degradation	Long-term degradation in mV/kh, **V%/kh**, mΩ cm^2/kh and mΩ cm^2%/kh

Unfortunately this is far from possible in every reported test. Often, only the information in **bold** in Table 1 was available, but sometimes essential information such as number of cells or operating temperature is missing. In Figure 2 the number of articles explicitly and implicitly (calculated from other parameters) stating specific parameters is shown for single-cell- and stack-tests. As seen, there is a noticeable lack of attention given to the area-specific-resistance (ASR) and in most cases the initial ASR, the degradation rate in

terms of mΩ cm^2/kh, and open-circuit voltage are in almost every reporting only accessible by estimation using Ohm's law, the Nernst equation and e.g. the Cantera software [58] (and thereby not accounting for any leaks). Certain information is understandably confidential by nature, but the widespread use of V%/kh as an indicator of degradation has already been questioned [59], and will be discussed further in the Discussion section of this paper. Likewise, the lack of data reported will be addressed.

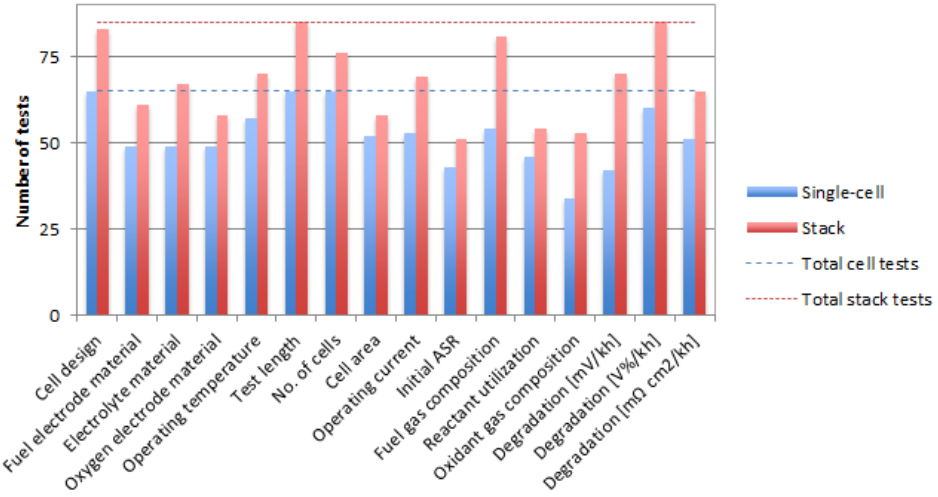

Figure 2: Data obtained from articles on single-cell or stack tests, either mentioned explicitly or calculable from other data mentioned.

3. Results

The number of accumulated test hours in this study is approximately 1 000 000 h, collected from 150 single-cell- and stack-tests. Please see the uploaded open-access database [2] for references and more details (download it for proper formatting). The data was mainly based on published articles, but conference proceedings and data from workshop presentations are included as well. Unpublished data from DTU, Topsoe Fuel Cell A/S and Haldor Topsøe A/S are included in the plots of this paper, but not in the open-access database. Only tests above 1 kh are included, and there has only been one prioritization, namely recently published articles. It should be kept in mind that most of the data originates from 2011-2015. It must also be noted that in the calculation of many of these values, a linear degradation is assumed between initial and final voltage measurement. This is of course a simplification, but a necessary one considering the amount of data.

In the following section a number of plots based on the collected information are given. There are many arguments against blindly comparing very different tests, which will also be discussed later in the paper. For instance, a 120-cell stack with 550 cm^2 active area cells running with natural gas cannot be directly compared to a 2-cell stack with 80 cm^2 active area cells running with H_2. Even if the latter has a much lower degradation rate and longer lifetime, the former is obviously closer to successful commercialization (depending on the intended application). Despite this, some interesting observations can still be made. Lastly, it is noted that not all companies are represented in the data due to lack of recent

publications, e.g. major ones such as Bloom Energy, Acumentrics, Aisin, GE, Redox Power Systems, etc. This will naturally decrease the accuracy of any predictions.

Degradation rate and lifetime

The degradation rate reported for stack tests are shown in Figure 3 with the degradation indicators V%/kh and mΩ cm^2/kh against the estimated test start date.

In fuel cell mode, for both indicators, the degradation rate appears to be decreasing with time. Using a simple linear regression one can estimate the average degradation rate of the reported tests, excluding outliers of Figure 3, to reach 0.25 V$_{\%}$/kh or 0.11 V$_{\%}$/kh by year 2017 and 2019, respectively. These numbers represents respectively the former NEDO target, 40 kh lifetime with end-of-life (EoL) of 90% of initial voltage [20,60-61], and the new NEDO target, 90 kh and 90% of initial voltage [62]. The Department of Energy has a similar target of 60 kh lifetime and an EoL of 82% of initial voltage by 2020 [63], i.e. 0.3 V$_{\%}$/kh. The SECA program reported similar targets [64]. The only mentioned ASR target of 4 mΩ cm^2/kh [3] is here predicted to be reached by year 2024. However, for a commercial breakthrough the *average* degradation rate does not necessarily need to reach the targets, it will likely be enough that just one or a few companies do so. On the other hand, a low degradation is not all that matters. The stack needs to be operated successfully for e.g. 40 kh or even 90 kh with the appropriate fuel gas type, and probably also with a certain number of thermal- and load-cycles. It is also noted that it is unknown if there is a tendency in the community to only report improvements, thereby skewing the trends observed here.

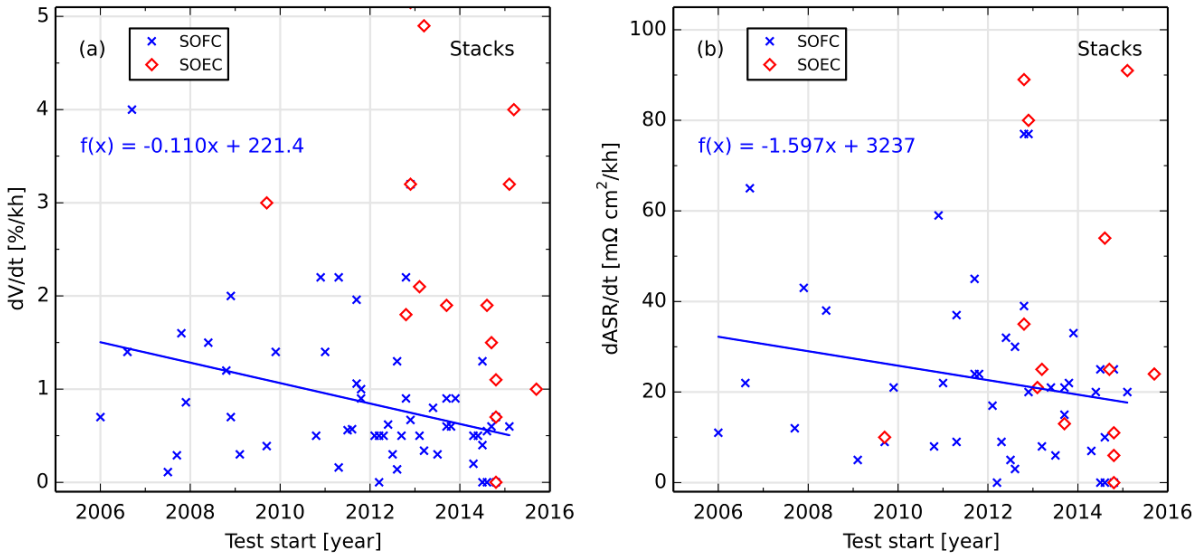

Figure 3: Degradation rate in (a) V%/kh and (b) mΩ cm^2/kh against the date the stack test was started (estimated by publication year and test length). The legend indicates the operation mode.

For reasons discussed in this paper it is near impossible to impose a fair “score” on a given test due to the multitude of influencing parameters and considerations. The authors of this paper hesitate to even mention the “best” tests, but in the published database the

three longest running stack tests and the three stack tests with lowest degradation, for each category, are given. At the time of writing, for test length of SOFC stacks, Forschungszentrum Jülich (FZJ) [20] and HEXIS [65] tops the chart with 65.2 kh (published, but has been continued beyond this) and 37 kh, respectively (see Figure 5a). In terms of degradation, several have published apparent zero degradation (MHI [66], SOLIDpower [67], Elcogen [68]), albeit only with 7 kh, 4.2 kh and 2 kh test length, respectively. In electrolysis mode, fewer tests have been reported. The degradation rate is generally higher than it is for fuel cell mode and is quite scattered. For SOEC stacks, ElfER have reported 10 kh and 8.2 kh for stacks produced by SOLIDpower [67] and Topsoe Fuel Cell [69], respectively. Degradation of SOEC stacks is topped by FZJ [70] with negative degradation rate (activation) and 11 mΩ cm^2/kh degradation in two ~2 kh tests. For single-cell tests, please see the database.

One can also estimate the predicted lifetime of each test if linear degradation and an EoL are estimated, in this case to 90% of initial voltage for SOFC mode and 1.5 V for SOEC mode. These somewhat arbitrary values can be changed in the uploaded database if desired. This approach is probably overly optimistic, as it does not account for emergency shutdowns or accelerated degradation later in the stack's life etc. Also, tests with a reported degradation rate of 0 mV/kh or even activation has here been approximated to an estimated lifetime of 90 kh, which may be unrealistic. In any case, as seen in Figure 4, the average estimated lifetime is increasing in recent years and for SOFC mode, again assuming a linear improvement and excluding tests with excessive degradation (>5 $V_{\%}$/kh), the average estimated lifetime will reach 40 kh by year 2018 and 60 kh by 2026. However, it becomes clear that to reach 90 kh in the foreseeable future, we would need to improve the lifetime faster than linearly. Again, the same arguments apply concerning a technology breakthrough based on the community average vs. just a single company reaching these targets.

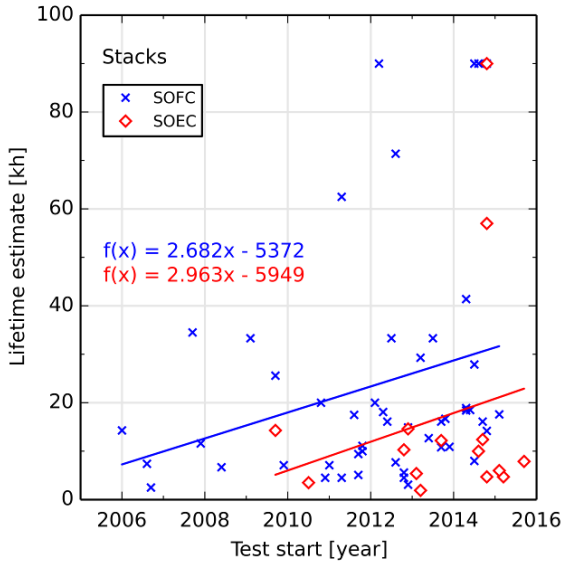

Figure 4: Estimated lifetime of each test against the estimated start date of the test.

The legend indicates operation mode.

Cell design

The planar fuel electrode supported cell design type is heavily favored among both cell- and stack-producers worldwide, which is reflected in Figure 5. However, it does not seem that one design is more suited for long-term testing than another, but rather that all types of design work. It is also seen that although the average estimated lifetime has reached 30 kh (Figure 4), the actual test length is rarely above 10 kh for both stack- and single-cell-tests. Long-term tests are expensive, especially for stacks, and time-consuming in nature, which is why degradation rate indicators and the estimated lifetime discussed before are interesting alternative measures to actually testing until the stack or cell fails. It is noted that tests showing high degradation rates initially would tend to be terminated prematurely, so the apparent correlation between low degradation rate and long test length may be tainted.

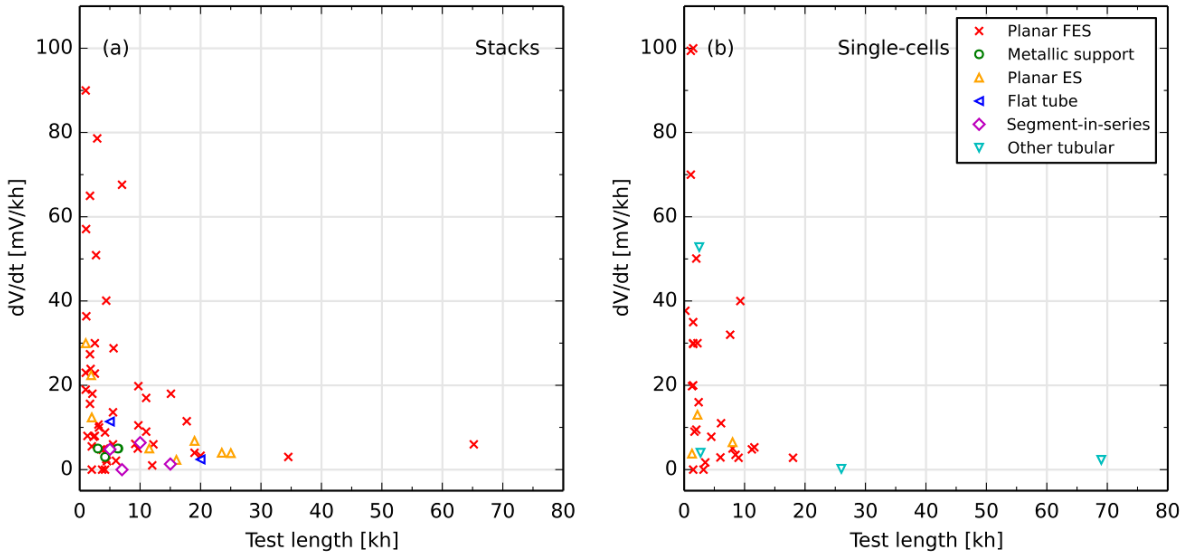

Figure 5: Degradation rate in mV/kh against length of the reported (a) stack- or (b) single-cell-test. The legend indicates the design of the cells, where FES stands for fuel electrode supported and ES for electrolyte supported.

Electrode materials

As seen in Figure 6a, the more recently employed oxygen electrode material, LSCF, is commonly utilized in lower operation temperature tests, 700-750 °C, while LSM and other materials are commonly used at higher temperatures. This illustrates that, once again, lifetime and degradation rate is not all that matters. Producers are well aware that a lower

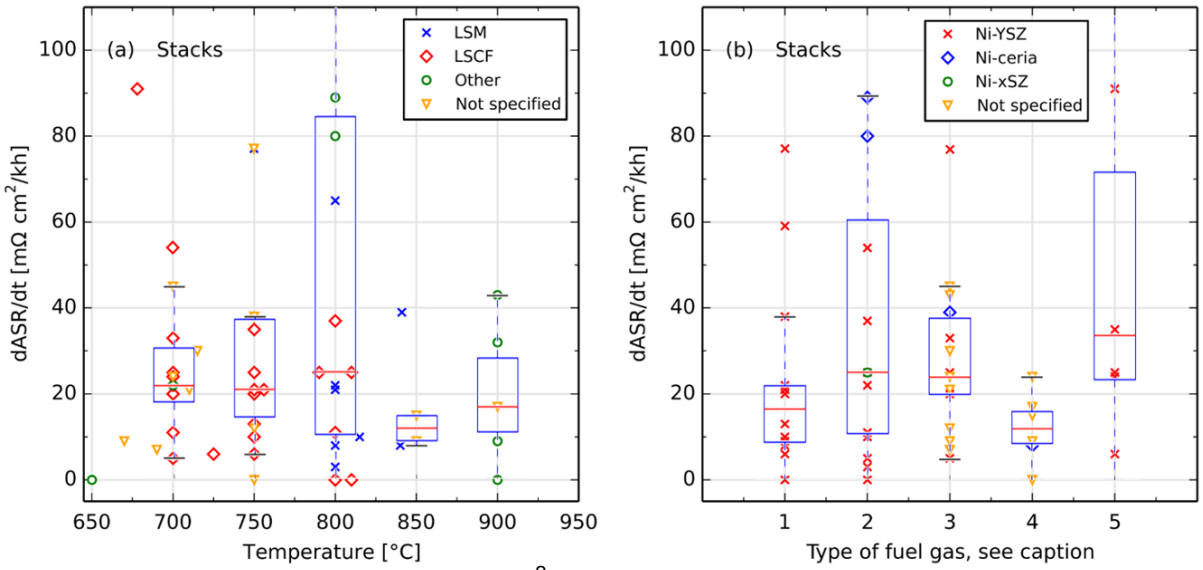

Figure 6: Degradation rate in mΩ cm^2/kh against (a) temperature for the most common oxygen electrode materials, and (b) against different types of fuel gas for the most common fuel electrode materials. Type 1: 90-100% H_2 balanced by H_2O for SOFC or 90-100% H_2O balanced by H_2 for SOEC; type 2: 0-90% H_2 balanced by H_2O for SOFC or 0-90% H_2O balanced by H_2 for SOEC; type 3: H_2/H_2O with various hydrocarbons; type 4: Natural gas, CH_4 or propane; type 5: CO/CO_2. Boxplots are overlaid to visualize trends.

operating temperature is also desired, as this will allow for e.g. cheaper IC materials and a simpler balance-of-plant. As seen in Figure 6a, one reported test sticks out. Elcogen reported a stack test operating at 650 °C with La-Sr-Co oxygen electrodes with approximately zero degradation during the 2 kh the test ran for [68]. For further details, please see the mentioned database. In Figure 6b the overwhelming popularity of Ni-containing fuel electrodes is clear. It is also seen that the degradation rate is generally lower for tests operated with pure reactant or natural gas, although the difference is minor.

Area-specific resistance

For some time now it has been speculated that many degradation mechanisms are overpotential driven [31,46,71-72], e.g. a higher overpotential of the fuel electrode will lead to more degradation of the fuel electrode. Most reports about long-term tests do not include information as to the separation of resistance or degradation for each component, but in many cases the ASR under current right at the start of the test is calculable using Ohm's law. Plotting this initial ASR value against the overall degradation rate, Figure 7a, seems to confirm that lower resistance will lead to a lower degradation rate. In Figure 7b, it is observed that most SOFC tests are operated with an overvoltage of 100-300 mV, while SOEC tests are operated with much higher overvoltage. This may contribute to the generally higher degradation of cells and stacks operated in SOEC mode.

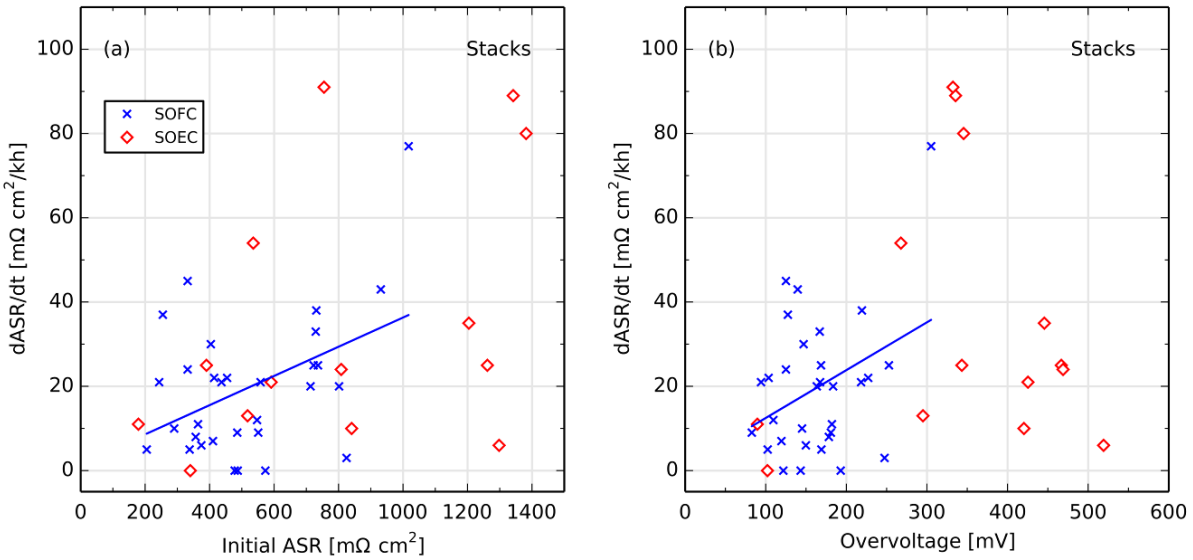

Figure 7: Degradation rate in mΩ cm^2/kh against (a) the initial ASR in mΩ cm^2, and (b) the overvoltage in mV. The legend indicates the operation mode.

4. Discussion

The discussion of an ideal degradation indicator has been ongoing in the community for a number of years, see for instance Gemmen et al. [59]. The following should be seen as a continuation of that discussion.

The degradation indicator

The by far most commonly used parameter in the community to describe degradation is the loss of voltage in percent relative to the starting voltage per 1000 h (V%/kh). It is so widely accepted as a degradation indicator that some authors even neglect to specify voltage, but instead simply note "%/kh". This is an easily obtainable and quickly calculable parameter that is useful as it holds information on the conversion of energy. However, the parameter also has flaws. As it only takes the voltage and length of the test into account, one cannot compare cells with different initial performance or different operating conditions. If the test is operated mildly with poor performance, i.e. a low production of electricity or gas, V%/kh would be low, but the purpose of the system has not been optimized (depending on the intended application). Furthermore, if for instance the voltage decreases (or increases for SOEC) rapidly in the first couple of hundred hours and then regains performance in the last couple of hundred hours, then simply stating the V%/kh from the initial voltage measurement to the last, would be misleading. Moreover, the reporting of the value is also quite subjective. Some authors choose to use the last e.g. 500 h of the test, while others disregard the first e.g. 300 h. The history of the cell or stack before initiating the constant-conditions-test will also have an effect, but this fact is rarely mentioned. As noted earlier, due to the large dataset, in this study the entire (constant-conditions) test is generally included in the calculation of the number, but any nonlinearity of performance over time is not considered.

Unfortunately many projects and published articles also refer to targets using this unit. For instance, one of the SOFC degradation targets most commonly referred to in the past 5 years was 0.25 V%/kh, i.e. 10% loss in voltage over 40 000 h [20,60-61].

Alternative degradation indicators

A better parameter would be the increase in ASR per time-unit (dASR/dt), i.e. mΩ cm^2/kh. With this value, the change in performance, the test length and the current are taken into account, but the initial performance is not. This would allow for better comparison of degradation rates at different operating conditions. Using current density-potential (i-V) plots, the ASR can be determined from the secant or the tangent (using electrochemical impedance spectroscopy) at the desired operating current density. The two methods often yield different values due to non-linearity in i-V curves, but it can also be determined quickly through Ohm's law, which will yield the same value as the secant-method. dASR/dt is rarely mentioned, but has in this study in many cases been calculated using Ohm's law and an estimated value for the OCV. As pointed out by others [59], one should carefully consider whether the experimental voltage or the ideal Nernst potential is used, as the former will include certain experimental effects (e.g. leaks) while the latter will not. Knibbe et al. mentioned this parameter as a target, i.e. 4 mΩ cm^2/kh [3].

Alternatively, one could use the loss in ASR normalized to the starting ASR per 1000 h (ASR%/kh). However, if the initial ASR is high, ASR%/kh would be small. So, this number does also not yield a fair comparison for different systems. The instantaneous ASR rate is attractive to use to visualize whether the degradation is accelerating or decelerating, but it does not constitute a viable alternative as a descriptive single-value indicator of degradation for an entire test. The average ASR throughout the test is technically not an indicator of degradation, but rather of performance (e.g. energy efficiency) throughout the entire test. To describe a whole test, it would be necessary to mention the deviation from the average as well. It is also quite sensitive to the test length, so standardizing this parameter would be needed.

Considering the energy aspect would reveal even more information than just using voltage or ASR. Different producers on the market have different customer segments, so in a fair comparison one would include the intended power output for the system in terms of electricity or fuel product and intended lifetime, e.g. a specific µ-CHP technical target could be 5 kW operational for 5 years (788.4 GJ or 219 MWh) with 10 thermal cycles, 10 load cycles and an average energy efficiency of 50%. The energy efficiency is more difficult to calculate or estimate, but the information within this parameter is more directly relevant for the customer, i.e. how much energy is wasted? If the target is simply an amount of energy produced, e.g. 788.4 GJ in the example above, one could calculate the number of "re-buys" (replacing the stack) to reach the target, i.e. total power produced divided by the target, but it would be necessary to include the capital cost of the system as well.

While the simple reporting of V%/kh is a useful value to compare identical systems, using slightly more inputs in the degradation indicator (e.g. ASR/kh) would paint a clearer picture when comparing different systems. However, as discussed, it is difficult, if not impossible to identify one single parameter that includes all the necessary information for every situation. The ideal parameter for the customer would be the amount of energy produced (gas or electricity) per monetary unit spent (e.g. J/€). In the case of SOEC, a unit of L/€ might be more practical. Such a value is what the market or the customer is interested in, but it does require inputs such as system price, gas/electricity input price and measurements or estimations of the output product. Due to the lack of a developed market

with listed system prices from producers this value could not be obtained in the present study. In certain cases it is possible to estimate the electrical energy produced or consumed (SOFC or SOEC, respectively) and the amount of gas consumed or produced (SOFC or SOEC). For SOEC operation below the thermoneutral voltage, the amount of heat supplied to the system should ideally be included as well. All in all, this can yield an expression of efficiency measured as kWh/m^3, which can be interesting to compare for different systems. The notion can be further investigated by estimating the total lifetime of the test if the EoL is assumed for instance to be 90% of initial voltage for a SOFC-unit. This can give an estimated lifetime had the test continued running. The total amount of electricity produced (SOFC mode) at the predicted EoL relative to the total amount of gas consumed can then be calculated. Estimations for electricity prices and gas prices can be used to calculate an estimated profit at the EoL for the test. Unfortunately such calculations are only possible if many of the parameters listed in Table 1 are available and as already discussed, it is rarely so. Nonetheless, in a few cases this was possible and is available for viewing in the open-access database. For H_2, kWh/m^3 is typically 1-2 for SOFC and 2-3 for SOEC.

Standardized reporting of long-term tests

As mentioned, the subject of a fair degradation indicator has been discussed before by others [6,59,73], many of whom have also pointed out the inherent drawbacks of using V%/kh. However, the degradation rate normalized by the initial voltage is still the preferred value in the community. To overcome the issues of comparing different tests, the testing itself would have to be standardized. This has been attempted in the FCTESTNET [74] and the FCTESqa [75] programs, where a set of particular conditions were specified for SOFC operation with a few chosen fuel gas types. The subject is also currently being investigated by the on-going SOCTESqa program [76], which also considers SOEC and reversible operation. Many companies and research institutes naturally operate with various internal quality assurance (QA) standards, like described by Haanappel et al. from FZJ [77-78]. Such internationally recognized QA standards, like the ISO9000 series, are important first steps in the comparison between different systems. Still, one standard has not yet been adopted by the community. Unfortunately, with the high degree of variety from system to system, it seems near impossible at the present moment to standardize testing in a manner that would be fair to all systems. In the meantime, one alternative would be to standardize the reporting of tests, so that it is clearly visible when comparisons can be made. Furthermore, this would quickly convey information on the test in general as well. In Table 2 a suggestion for a simple standardization (assuming galvanostatic operation) is shown and the table has been uploaded for easy copy and paste [79].

Table 2: Suggested standardized reporting protocol for long-term tests.

Cell producer:		Cell design:	
Stack producer:		Fuel electrode:	
Testing organization:		Electrolyte:	
Date of test start:		Oxygen electrode:	
Operation mode:		Interconnect:	
Length of test:	kh	Average power:	kW
Temperature:	°C	OCV and initial voltage:	V
Current density:	A/cm^2	Initial ASR:	mΩ cm^2
Fuel gas composition:		Total degradation:	$V_{\%}$/kh mΩ cm^2/kh
Fuel gas flow:	L/h/cm^2		
Fuel gas utilization:	%	Average efficiency (+ std. deviation)	%
Oxidant gas:		Total production:	kWh L (of e.g. H_2)
Oxidant gas flow:	L/h/cm^2		
Oxidant gas utilization:	%	Degradation mechanisms:	
No. of thermal cycles:		Notes:	
No. of load cycles:			

Keeping the database up-to-date

The plots shown in this paper are merely examples of a few interesting comparisons and we invite the reader to compare and plot other parameters perhaps more relevant. The open access degradation and lifetime database has been uploaded [2]. Anyone interested in using the data are welcome, but we ask that you cite this paper or the above-mentioned DOI in doing so. We also encourage companies and research institutes to contact the authors at enrgk-soctests@dtu.dk and supply data from your single-cell- or stack-test with either the proposed standardized reporting format or in similar format as the data in the database. This will keep the database up-to-date for the benefit of the solid oxide cell community.

5. Conclusion

A quantitative review of the current international status of lifetime and degradation for solid oxide devices has been presented. The study was based on a large dataset collected from more than 150 publications, and with the help of the community the database will continue to grow as more data is published. While the majority of cell- and stack-tests are limited to 10 kh, it was found that degradation rates in recent years have been steadily decreasing and an estimation of the predicted lifetime of the average stack is expected based on a linear trendline to reach the target of 40 kh before 2020, and 60 kh by 2026. However, targets will most likely be met even sooner for individual cases, which will facilitate market penetration. Several other observations based on the data are discussed.

Moreover, it was discussed how to report tests most efficiently so as to enable easy comparison between different systems. Due to the large array of differing parameters between systems and tests, a standardized reporting protocol in the form of a simple table is suggested. The solid oxide cell devices community is encouraged to adopt this standardized form of reporting tests.

6. Acknowledgements

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